

Design and Testing of a Control Strategy for a Large, Naturally Ventilated Office Building

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Abstract

The design for the new Federal Building for San Francisco includes an office tower that is to be naturally ventilated. Each floor is designed to be cross-ventilated, through upper windows that are controlled by the building management system (BMS). Users have control over lower windows, which can be as much as 50% of the total openable area. There are significant differences in the performance and the control of the windward and leeward sides of the building, and separate monitoring and control strategies are determined for each side. The performance and control of the building has been designed and tested using a modified version of EnergyPlus.

Results from studies with EnergyPlus and CFD are used in designing the control strategy. EnergyPlus was extended to model a simplified version of the airflow pattern determined using CFD. Wind-driven cross-ventilation produces a main jet through the upper openings of the building, across the ceiling from the windward to the leeward side. Below this jet, the occupied regions are subject to a recirculating airflow. Results show that temperatures within the building are predicted to be satisfactory, provided a suitable control strategy is implemented uses night cooling in periods of hot weather.

The control strategy has 10 window opening modes. EnergyPlus was extended to simulate the effects of these modes, and to assess the effects of different forms of user behavior. The results show how user behavior can significantly influence the building performance.

Introduction

The control system development study presented in this paper continues previous work^{1,2} on the design of the natural ventilation system for the new San Francisco Federal Building (SFFB). The present study, which determines the optimal control strategy for the low energy cooling system, is a fundamental component in the achievement of maximum performance of the passive cooling system.

The control strategy described in this paper is part of an effort to create a low energy indoor climate control system, or building management system (BMS), with the following characteristics.

- Ability to control indoor airflow velocities.
- Effective use of the building internal thermal mass for cooling.
- Rational use of heating energy.
- Ability to control indoor conditions during storm, rain and high wind periods.
- Unobtrusive and as simple as possible.

This paper begins with a description of the components of the indoor climate control system in §1.

The cross-ventilation air flow is described in §2, which considers the impacts of the user controlled windows. The control modes are defined in §3. This includes the rationale for the choice of the modes and the definition of the building in terms of its windward and leeward sides. The simulations are described in §4 and the results are given in §5. Conclusions are drawn in §6.

1. Components of the indoor climate control system

Figure 1 shows a section across a typical floor of the naturally ventilated portion of the building. As shown in our previous study^{1,2}, use of the stack effect to supplement wind-driven flow does not improve the cooling performance of the building significantly, given the favourable wind climate that exists in San Francisco. The design uses wind-driven cross-ventilation to cool and remove pollutants from the open-plan spaces.

Wind enters through windows on the NW and SE facades. The upper windows are controlled by the BMS and the lower windows are controlled by the users. The orientation of the building is such that the usual flow is from the NW bay to the SE bay (see figure 1). This wind-driven flow provides the main cooling in the warm season, either directly during the day or by night time precooling of the

ceiling slab. The aim of this study is to develop a strategy for controlling the windows so that desired indoor temperatures are maintained throughout the year.

INSERT FIGURE 1

Heating is provided by a perimeter baseboard system. There are nine trickle vents under selected baseboards on the exterior wall of each bay. When there is need and the outside temperature allows it, outside air can also be used to warm the building. Essentially all of the SE façade is glazed. Although these windows are shaded by an external metal scrim (see figure 1) there is a significant amount of passive solar heating through these windows at the beginning of the day.

The cooling source is the outside environment either by direct daytime heat removal using ventilation air, or through an exposed concrete ceiling slab that can be cooled during unoccupied hours using outside air. This cooled thermal mass can be used as a heat sink for daytime gains (the standard night cooling principle), both to reduce maximum indoor temperatures and to delay the time of the maximum temperature until after the end of the working day.

The building will be controlled by a combination of user and automated window adjustment. The automated building management system (BMS) has exclusive control over the baseboard heating system. As will be discussed in §5, the users can significantly change the effective opening area, affecting the result of the BMS decisions. In order to avoid continuous, possibly distracting and wasteful, control actions, the BMS will make adjustments, heating set points, window positions, every 10 minutes. This time interval is discussed below and maybe adjusted when the building is commissioned.

2. Optimal cross-ventilation airflow

The basic ventilation is wind-driven cross ventilation from the windward side to the leeward side of the building. Usually, but not always, the NW façade is at positive pressure and inflow occurs on that side of the building. The control strategy uses pressure data to determine the windward side (WS) and

leeward side (LS), which, of course, depends on the actual wind direction. The controls are based on the instantaneous WS and LS designation.

The CFD analysis of the natural ventilation airflow, performed by P.F.Linden & G.Carrilho da Graca¹ showed that the inflow air attaches to the ceiling and partially “short circuits” the windward bay, exiting through the windows in the leeward bay. The initially proposed geometry of the user operated windows contributed to this effect by generating an inflow jet that attached to the WS user windows and joined the BMS operated window inflow jet. Under these conditions the WS users had limited control over their environment. To solve this problem, a flow deflector was introduced on the lower windows, which directs the inflow through them into the occupied zone. This allows WS occupants to influence their local environment.

This modification to the window design allows for an elegant approach to the cross-ventilation control strategy, since it disrupts the pure sequential organization of the airflow from windward to leeward. This initial flow pattern caused LS users to be strongly affected by the control actions taken by WS users. With WS users able to adjust their local flow, by opening or closing a window that directs flow to their work area, the BMS can address the needs of the LS users (see figure 2).

INSERT FIGURE 2

In addition to this separation, and as a result of the approximately symmetrical layout of the floor plan, we developed the control strategy using a Windward-Leeward reference system, as opposed to a NW-SE bay reference. This decision is a consequence of the importance of the flow pattern in the system behaviour and our desire to simplify the control system. Table 1 shows the four possible states that result from this approach. By basing the control system on the wind direction the number of possible system states is greatly reduced.

INSERT TABLE 1

The geometry of the building natural ventilation system, and the dominance of wind versus buoyancy, require special considerations over the opening geometry whenever heating is on. In particular, it is necessary to avoid exhaustion of air, heated by the baseboard system, through the adjacent trickle vents on the leeward side. For this reason, whenever heating is on, only the trickle vents on the windward side will be opened. Since the BMS and user operable windows are close in height, stack

driven ventilation is only important when the wind velocity is very low or perpendicular to the building cross-ventilation axis and the trickle vents are opened.

Figure 2 shows the floor subdivision used to define the controlled zones. The basic control unit or subdivision is one half of the floor shown (each floor has two BMS systems, one for each set of five “slices”, numbered 1-5 in figure 2). The window opening strategy reflects the fact that inflow geometry is the governing parameter in the airflow distribution. Each floor measures approximately 107x19m. Each half of each floor in the building is treated separately and divided into 5 slices numbered as shown. Each slice contains four user operated and two BMS operated windows. The side view on the bottom of the figure shows the control structure, using the partial short circuiting of BMS window inflow into the windward zones (labeled 1). The criteria followed when defining the opening modes were:

- Use distributed WS inflow openings to distribute the inflow across the floor plan and reduce inflow velocities
- Use the LS outlet area to control the flow rate
- Minimize operation of openings (by ensuring continuity between opening modes, avoiding open-close-open sequences on a particular window group as the system increases opening area)
- Minimize window positions, in order to simplify the mechanical actuator system (three positions are used: closed, half open and fully open)

The airflow control system was structured in an opening mode table, and the twenty BMS operable windows on each bay of the floor (2 per “slice”, 5 “slices” on each side, leeward and windward) were grouped for simplicity. The grouping criterion was optimal flow distribution. Figure 3 shows a schematic representation of the ten opening modes used. The positions of the openings are shown as fractions of the maximum opening size (between zero and one). There are two groups of trickle vents on each bay: “slices” 1, 3, 5, and “slices” 2, 4. The window groups are:

Group 1 - the two motorized windows in slice 3;

Group 2 - the four motorized windows in slices 1 and 5;

Group 3 - the four motorized windows in slices 2 and 4.

INSERT FIGURE 3

A mode table was written with the opening modes, denoted by the mode number MDN, ordered by effective opening area and weather/defensive criteria (see tables 2 and 3 for grouping and characteristics of the modes). This organization allowed for a control strategy that reflects the existence of the several system components mentioned above. On receipt of a request for increased heating or cooling, the ventilation system refers to the opening table and adjusts the flow by incrementing or decrementing the mode number.

Although the users have access to operable windows, it was decided that the BMS system would be used to ensure 50% of the regulatory minimum outside air amount. As a consequence of this decision, and of special outside conditions, upper and lower limits are placed on the opening mode number depending on the following limiting factors.

- A lower limit is used in order to ensure minimum outside air.
- An upper limit is used whenever the wind is strong, during rain periods or when the baseboard heaters are turned on in both bays.

The modes are organized as follows – see also tables 2 and 3. First, the modes are divided into storm (MDN 1 and MDN 2), heating (MDN 3 and MDN 4) and cooling modes (MDN 5-10).

When heating is on in both bays or it is raining then $MDN \leq 4$.

When both sides are in cooling mode then $MDN \geq 5$.

Within these subdivisions, the control modes have further constraints at times of high external wind speeds. The first high wind opening limiting mode is triggered by:

If $\Delta P > 60$ or $V_{wind} > 20 \text{ m/s}$ then $MDN \leq 8$.

The second high wind opening limiting mode is triggered by:

If $\Delta P > 130$ or $V_{wind} > 25 \text{ m/s}$ then $MDN \leq 6$.

The storm mode is triggered by:

If $\Delta P > 300$ or $V_{wind} > 30 \text{ m/s}$ then $MDN \leq 2$.

For a given pressure difference (ΔP), the effective opening area A^* and resultant flow rate F is given by

$$A^* = \sqrt{\frac{A_w^2 A_L^2}{A_w^2 + A_L^2}}, F = A^* C_D \sqrt{\frac{2 \Delta P}{\rho}} \quad (1)$$

where A_w and A_L are the opening areas on the windward and leeward sides, respectively.

The estimates of indoor ventilation parameters presented in table 2 show that the system has the desired characteristics, mentioned above. There is a continuous increase in opening size in each group of modes (see tables 2 and 3). There is a set of modes that controls the inflow and average occupied zone velocities (MDN 5-8). MDN 9 and MDN 10 are intended to be used when the wind is weak, or at night, when significant transfer between indoor air and the ceiling concrete slab are desirable.

INSERT TABLE 2 AND 3

2.1 Insuring minimum outside air

With the objective of having the BMS system ensure 50% of the minimum required outside air, we establish a decision process that starts from:

1- the measured the outside pressure difference ΔP .

- 2- an estimate of stack-driven ventilation (whenever the trickle vents are open, in the current control system this is equivalent to the heating being turned on).
- 3- the wind velocity (in order to prevent excessive opening size when the wind is perpendicular to the building and the pressure readings (ΔP) are close to zero but the transient ventilation is significant).

The algorithm estimates the total available pressure and determines the minimum opening size, which is translated into a mode between MDN 3 and MDN 10. When there is a storm (the system is in MDN 1 or 2), we rely on infiltration and user adjustment to provide minimum outside air. Buoyancy will only be considered when the heating is on in both bays (which implies the trickle vents are open). The total pressure difference (ΔP_T) available to drive the flow is composed of the sum of the factors mentioned above:

$$\Delta P_T = \Delta P + HOF \left(0.088 \left| \frac{T_W - T_L}{2} - T_{OUT} \right| \right) + 0.015 U_{WIND}^2, \quad (2)$$

where U_{WIND} is the outside wind pressure and HOF is a software “flag” that signals the buoyancy component should be considered. The third term in (2) is based on an experimental correlation to predict airflow in a building exposed to an incoming wind that is perpendicular to equal openings on opposite facades⁴. In order to keep the ΔP_T estimation simple, the effects of unequal opening areas on the two bays are ignored. In addition, the transient pressure term is not dependent on wind direction; this is an acceptable approximation because whenever the wind is not perpendicular to the openings the first term is one order of magnitude larger.

2.2 Impact of user window control

The lower windows shown in figure 1 are under exclusive user control. The user operable window area is approximately equal to the BMS controlled area. Therefore, users can significantly change the effective opening area (see (1)). For example, they can increase the effective opening size by a factor

of ten when the BMS is in MDN 1 or approximately double the effective area when it is in MDN 10.

If user control is not considered when designing the BMS two main problems can occur:

- Users on one of the two sides can affect the climate control on the other side
- Incorrect user control can lead to poor system performance, allowing for overheating of the interior space and concrete slab in summer and for heat loss to the outside in winter.

The first of these problems was addressed by making the outlet opening area smaller than the inlet area. From (1) this implies that the effective area is controlled by the size of the outlet rather than the inlet. Figure 4 illustrates the effect of this strategy. The three pairs of lines in the figure show the influence that LS and WS users have on the effective area (and consequently airflow rate). Three different opening areas are shown corresponding to MDN 5, MDN 7 and MDN 9 and the qualitative behavior is the same for each mode. As the amount of WS user area increases, the air flow (shown as the gray lines) remains almost constant. Consequently, the WS users obtain the desired increased local air flow when they open windows, but the effect on the LS users is minimal.

INSERT FIGURE 4

By contrast, adjustments by the LS users have a significant effect on the airflow and, consequently, on their indoor environment conditions as shown by the black lines in figure 4). In view of the previously mentioned partial short-circuiting on the inflow and the ability of windward users to adjust their local conditions, we conclude that the asymmetry in flow control is a beneficial feature in the system.

The impact of user behavior depends on the state of the BMS. The percentage of user opening on the total effective opening area decreases with increasing mode number. It will be shown below that, on hot days, when the BMS system tries to make optimal use of the cooled concrete slab, user opening can result in higher, and often uncomfortable, indoor temperatures. Clearly, the more general consequences of user behavior cannot be addressed by the control system. Therefore, appropriate information on building behavior and on appropriate actions in different situations must be provided to the users.

2.3 Modeling user behavior

Modeling user behaviour is a complex but essential task for the present study. In order to simulate the performance of the indoor environment control system with both BMS and user actions two types of user behavior were defined.

- **Uninformed Users (UU):** this type of user is modeled with behavior that is independent of BMS actions. If the conditions are warm, the user operable windows open sequentially (10% in each control time step of 10 minutes), up to 50% for indoor temperatures between 22 and 25°C, and up to 100% for temperatures above 25°C. If the conditions are cold, i.e. below 19°C, the user operable windows close by 5% each time step. On a typical day, when the air temperature in either of the two bays goes above 22°C, the users will open the windows. The windows then remain open until one of the sides feels cold (air temperature below 18°C), or until the end of the workday, when users always close their windows. Clearly, under our assumptions, uninformed users do not follow the BMS opening modes at all.

- **Informed Users (IU):** this type of user follows the BMS actions in an ideal way. Users only open their windows when the BMS is in one of the mild weather modes. Informed users follow the same decision and action trends as uninformed users but limit their opening amplitude in accordance with the BMS mode that is currently being used (i.e. linearly, from 0% in MDN 1-5 to 100% in MDN 10). In addition, whenever the BMS system uses night cooling, informed users will leave their windows fully open overnight.

3. Controlling indoor temperature

Table 1 shows the four temperature states that can occur in the two control zones of the building. We now proceed to describe and analyze the control strategies and rules used in each case.

3.1 Both sides cold

When both sides are cold, the auxiliary heating system will be on and the ventilation system will tend to minimum outside air in a progressive way, by reducing the window opening mode number by one in each control time step.

3.2 Both sides warm

In order to clarify the control principles used during daytime in the warm season, we present here a first order analysis of system behavior. To make this simple analysis possible we use two approximations.

(i) The only thermally active internal surface that will be considered is the concrete ceiling slab. This approximation is adequate since the remaining internal surfaces in the space have low thermal capacity and, therefore, tend to behave in an approximately adiabatic way since both sides are exposed to similar conditions.

(ii) The internal air is considered fully mixed. This is a significant approximation only acceptable for a first order analysis. For warm period control purposes we use a single temperature (the higher of the temperatures in the two bays) to regulate indoor conditions.

Under these approximations, the heat balance on a control zone (one half of one floor, see figure 2) is

$$h A_S (T_{IN} - T_S) + \rho C_P F (T_{IN} - T_{OUT}) = G, \quad (3)$$

where h is the convective heat transfer coefficient at the ceiling, T_{IN} is the fully mixed indoor air temperature, T_S is the ceiling slab average surface temperature, T_{OUT} is the outside temperature, C_P is the heat capacity of air at constant pressure, ρ is the air density, F is the volumetric ventilation flow

rate and G (W) is the total internal gain (solar, internal and heat conduction through the building envelope). The solution to (3) is

$$T_{IN} = \frac{1}{1 + \theta} \left(T_S + \theta T_{OUT} + \frac{G}{h A_S} \right), \quad \theta = \frac{\rho C_P F}{h A_S}. \quad (4)$$

Once the building is in operation, all the temperatures in this expression can be measured and used to determine whether to increase or decrease the normalised flow rate θ . The values of the heat transfer coefficient and the exposed area are unknown but are positive. Similarly, the heat gain, G , is positive (by definition) during the cooling season.

Qualitative analysis of (3) reveals that when the flow rate, F , and hence the normalised flow rate, θ , is increased, T_{IN} tends to T_{OUT} . Conversely, decreasing θ brings T_{IN} closer to T_S . The unknown heat gain parameter G also influences internal conditions; an increase in G results in increased T_{IN} .

Measurement of T_{IN} provides an indirect measurement of G , which is sufficient for control purposes.

Consider a first order expansion of T_{IN} in (4) in terms of θ . Differentiating T_{IN} with respect to θ and approximating $(1 + \theta)^{-1}$ by $(1 - \theta)$ yields

$$\frac{\partial T_{IN}}{\partial \theta} = \frac{T_{OUT}}{1 + \theta} - \frac{(T_S + \theta T_{OUT} + G/h A_S)}{(1 + \theta)^2} = \frac{(T_{OUT} - T_S - G/h A_S)}{(1 + \theta)^2}. \quad (5)$$

Solving (4) for $G/(h A_S)$ yields

$$\frac{G}{h A_S} = T_{IN} - T_S + \theta (T_{IN} - T_{OUT}), \quad (6)$$

Substituting (6) in (5) and simplifying yields

$$T_{INf} = T_{INi} + \Delta \theta \frac{T_{OUT} - T_{IN}}{1 + \theta}. \quad (7)$$

Here T_{INf} is the final internal temperature after an adjustment in θ of magnitude $\Delta \theta$. T_{INi} is the initial internal temperature. Equation (7) is an approximate analytical expression for the internal temperature after a control action. It shows that changes in T_{IN} resulting from a given change in θ have the same sign as, and are linearly dependent on, $T_{OUT} - T_{IN}$. On the basis of this analysis, warm-weather control rules were established as given in Table 4.

INSERT TABLE 4

3.3 Windward cold, leeward warm

As a result of solar gains on the SE façade of the building, the leeward side is often warm when the windward side is cold in the early morning on winter and mild season days. This is one of the situations where the interaction between the two sides must be considered. To meet the need for cooling on the leeward side, the ventilation mode number is increased by one. In order not to increase the cooling needs of the leeward users, but still address the need for heating on the windward side, the windward heating set-point is set to 18°C.

3.4 Windward warm, leeward cold

This case is the opposite of the previous case, but is not as problematic because the windward side users can address their needs by adjusting their operable windows without significantly changing the overall flow rate (see figure 4). For these reasons, in this situation, the control system will reduce the mode number by one and set the leeward heating set-point to a relatively high value (21°C) to ensure heating on this side.

3.5 Night cooling

Night cooling of the concrete ceiling slab is performed whenever the average indoor temperature during the warmer period of the previous day (11 am- 4 pm) was above 24°C. When night cooling is requested by the temperature control routine, the ventilation system uses the maximum allowed opening until the slab temperature is below 19°C or until the early morning of the following day (7 am).

In the future, the design team intends to incorporate weather prediction information in the control system, basing the decision to night cool on the predicted weather for the next day in addition to possible heat accumulation in the space during the previous day.

4. Simulation of system performance

In order to test and develop the low energy cooling system and its BMS control strategies, the building and user behavior were modeled using EnergyPlus with the COMIS³ natural airflow model. The model implemented to test the initial design principles¹ was used in the simulations presented below (including internal heat gains and building occupation schedule). This model has four zones: the two occupied bays (NW and SE), the meeting room in the middle of the floor plan and the space above the meeting rooms (see figures 1 and 2). The naturally ventilated portion of the building starts at the 6th floor, and adjacent buildings do not exceed this height, so all the naturally ventilated floors are exposed to the wind. The simulation used pressure coefficients measured in a boundary layer wind tunnel. Pressure coefficients representative of average wind pressure exposure in the naturally ventilated portion of the building were chosen.

The modularity of EnergyPlus allowed for the inclusion of a custom control subroutine that was used to simulate and tune the operation of the BMS system. The transmissivity of the metal shading scrim in the SE façade (see figure 1) was set to 30%. The five cases simulated are shown in table 5. Two typical mean weather years for San Francisco were used (TMY, airport data).

INSERT TABLE 5

5. Results

We begin by considering performance of the building controlled solely by the BMS, which is Case 1 in table 5. Our analysis of the two mean weather years showed that the critical times for cooling consist of sequences of no more than three hot summer days. At other times, the temperate climate presents no real problems for the control of the indoor environment. First we consider the behavior during a sequence of warm summer days and then we address the performance over the entire year.

5.1 Warm summer days

Figure 5 shows the predicted temperatures in the NW and SE bays and in the surface of concrete ceiling slab, over a sequence of hot days in July. The simulation time step is 10 minutes and the control algorithm updates the ventilation mode number every step time. The results are plotted as 30-minute averages. The first day shows typical behavior on a mild day when the external temperature stays below 20°C. As can be seen from the figure, between 10am and 2pm the BMS system is in MDN 8, showing that cool outside air is removing internal heat gains. The interior temperatures remain comfortable throughout the day.

INSERT FIGURE 5

The second day is a typical warm day in which the external temperature reaches almost 30°C. The BMS system selects the minimum daytime mild/warm mode (MDN 5) to optimize the cooling produced by the ceiling slab. The air temperatures in the bays exhibit two different behaviors during the day. During the morning $T_{aSE} > T_{aNW}$, as a result of solar gains in the SE façade. For wind from the NW, the air stream is attached to the ceiling slab until it enters the SE bay and in the afternoon $T_{aSE} < T_{aNW}$, as a result of the cooling of the air stream by the slab. The maximum internal temperature is less than 26°C.

Similar system behavior occurs on the following two warm days. During the unoccupied night time periods, the system promotes night cooling by selecting the maximum opening mode (MDN 10).

Figure 5 shows that the slab temperature increases over this period and the effectiveness of the night cooling diminishes with time.

The third day clearly illustrates the performance of the control system; even with an outside temperature of more than 34°C the inside temperature is below 29°C. On the fourth day, the interior temperature is almost the same as on the previous day, although the peak external temperature has decreased from 35°C to 30°C. However, our analysis of the weather data shows that occurrences of four or more consecutive days with maximum temperatures above 30°C are very rare.

INSERT FIGURE 6 AND FIGURE 7

Figure 6 shows the average dry resultant temperature in the two bays for the same days as shown in figure 5. (The dry result temperature is the mean of the air temperature and the radiant temperature and is a reasonable proxy for thermal comfort.) The dry resultant temperature shows the same trend as the indoor air temperature, but is 1-2F lower. As expected, air flows from NW to SE for most of the time during these summer days. However, there are occasional changes in wind direction, such as the one visible at 1pm on the third day. As a result of this wind direction change, the dry resultant temperature in the SE bay increases as the airstream cooled by the slab is replaced by a stream of warmer outside air.

To illustrate the opposite extreme, Figure 7 shows the behavior over the same days, but with no BMS and “uninformed” user behavior (Case 5 in table 5). The gray squares labeled MDN indicate the fraction of user operable windows that are opened at a given time, varying between 0 (closed) and 10 (fully opened). In this case, the internal temperatures track the external temperature closely, peaking at about 34°C on the hottest day. Comparison with figure 5 shows that the BMS achieves a reduction of about 6K over this worst case. This is a significant reduction, which is sufficient to provide comfortable internal conditions throughout the year.

Figure 8 shows a comparison of the predictions of comfort temperatures for four intermediate control strategies, Cases 2-5. It is clear that uninformed users can have a significant negative impact in indoor climate conditions, with much larger diurnal temperature changes for Cases 4 and 5 compared to Cases 2 and 3, which either have no user action or informed user action. According to our assumptions, uninformed users make limited use of the cooled slab, resulting in higher indoor temperatures. Since the area of user-operable openings is comparable to the BMS controlled area, this impact extends to Case 4. The absence of night cooling results in a 1K increase in the temperature on the warmest days.

INSERT FIGURE 8

5.2 Annual performance

Calculations for the two mean weather years were analyzed to determine the times when the building is uncomfortable. The heating system is adequately sized and we restrict our attention to the times

when the internal temperature is high. EnergyPlus simulations were performed for the 5 cases in table 5, and the number of hours in the expected operation schedule of the building (taken to be 0800-1800) that exceeded a given temperature was calculated. The results are given in table 6.

The number of hours above 26°C is small, independent of the user behavior. Even for the worst case (Case 5) a maximum of 4.2% of the daytime hours have temperatures above this value. This corresponds to 15 days. For the best case (Case 2) this is reduced by a factor of 2, to 7 days. If the threshold is set to 28°C, the best case has warmer temperatures for 2.3 days.

Table 6 also shows that the SE bay has higher temperatures than the NW bay. These temperatures are found to occur in the morning as a result of solar gains through the façade. In order to reduce this gain a metal scrim will be erected along the SE façade, as shown in figure 1.

The effects of varying the solar and optical transmissivity of the SE metal scrim between 30 and 60% for Cases 2 and 5 are shown in figures 9 and 10.

INSERT TABLE 6

INSERT FIGURE 9 AND 10

Table 7 shows an additional indicator of thermal stress obtained by summing, for each hour with temperature above a given value (24, 26 and 28 as in table 6) the number of degrees that the inside temperature exceeds the threshold:

$$\sum_{\text{hours with } T > T_T} (T - T_T) \quad (8)$$

where T is the temperature in each bay during occupied hours and TT is the threshold used to obtain each column in the table. In order to improve readability, the values in the table from the calculation (8), for the two years simulated, divided by 1000.

The results obtained are very similar to table 6, still, this indicator shows higher sensitivity, allowing better distinction between cases 1, 3 and 5. For example the first column of table 7 shows an increase in thermal stress of 151% between cases 1 and 5, up from 91% in table 6.

INSERT TABLE 7

Figure 9 shows the effects on warm days. Doubling the scrim transmissivity increases the temperature by about 2K. The effect is most pronounced before noon, but there is a noticeable effect throughout

the day. Figure 10 illustrates the typical effect on winter days. As a result of the SE façade orientation, the solar gains are significant in winter and result in excessively high air temperatures, especially in the case with 60% scrim transmissivity. Figure 10 shows that the BMS tries to reduce overheating in the SE bay by increasing the selected window opening mode and, consequently, the airflow rate (by selecting MDN ≥ 6), and decreasing the heating set point in the NW bay.

Table 8 shows the effects of doubling the scrim transmissivity. The discomfort, as indicated by the number of hours above 24-28°C increases by ~100% in the SE bay (compare with table 6).

INSERT TABLE 8

INSERT FIGURE 11

Figure 11 is a graphical representation of the results shown in table 6. It shows the percentage of hours in excess of the threshold temperature for each of the 5 cases in table 5. Night cooling (Cases 1, 2 and 4) has a significant impact in indoor climate conditions, giving significantly cooler conditions. It is particularly effective in reducing peak temperatures between 24°C and 26°C.

Operation of the BMS system always results in improved indoor climate conditions, even when users behave in an uninformed way (Cases 4 and 5). In San Francisco's mild windy climate, informed user behavior (Cases 2 and 4) is essential only in the warmer hours. Because days with warm hours ($T_{OUT} > 25^\circ\text{C}$) are infrequent (on average, 20 days per year) the impact of incorrect user behaviour is not as significant as might be expected from a simple analysis of the results in figures 7 and 8.

Conclusions

This paper describes the development of a control strategy for the window openings on the naturally ventilated floors of the proposed San Francisco Federal Building. The proposed control strategy is tested by simulating the building with EnergyPlus.

The control strategy uses the results of previous CFD calculations¹ on the wind-driven cross ventilation. This study showed that the air stream attaches to the ceiling and is effective in exchanging

heat with the exposed ceiling slab. Window opening is used to control the amount and distribution of the airflow.

This control strategy was tested by simulating two years of weather data using EnergyPlus and COMIS³. The results show that the mild San Francisco climate produces comfortable interior conditions for most of the year. The main problem is modest overheating during a sequence of warm summer days. Night cooling and optimal use of the chilled slab during the day is an appropriate strategy to deal with the warmest periods. The indoor climate conditions in the SE bay of the building are very sensitive to the transmissivity of the shading scrim.

This building has a significant number of user-controlled openable windows. The simulations show that user behavior can have a significant impact on the performance of the building. Uninformed users can increase the number of warm hours by almost an order of magnitude over informed users. Since informed user behavior may be counter-intuitive, such as closing windows to optimize slab cooling on hot days, optimal performance requires that users receive education on the operation of the building. As detailed in the paper, the proposed control strategy should give a comfortable indoor climate for the vast majority of the time. With good user behavior, it is expected that the inside temperature will exceed 28°C for less than 20 hours per year.

Acknowledgements

Erin McConahey, Rick Lasser, David Summers and Michael Holmes provided assistance and advice at various stages of the work. This work was supported by the U.S. General Services Administration and by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Federal Energy Management of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Figure 1.

Section of a typical floor.

A section from the NW bay (left) to the SE bay (right), showing the air-conditioned meeting rooms in the center. The lower operable windows visible on both bays are controlled by the users. The upper windows are controlled by the building management system (BMS). The user operated windows open 10cm, the BMS operated windows open 20cm. There are two user operable windows for every BMS operated window. The metal shading scrim that covers the South-East façade of the building is shown on the right.

Figure 2.

Schematic layout of the control system on a typical floor.

Figure 3.

Schematic representation of the aperture modes.

Each floor of the building is divided into two symmetrical sides. The figures show one half of one floor. The black square in the center of the figures is an elevator/service core that creates an obstruction to cross-ventilation airflow.

Figure 4.

Variation of effective opening area (A^* , expression (1)) with user opening.

The three pairs of lines (from bottom to top) show the effective area for, respectively, opening MDN 5, 7 and 9. The gray lines are obtained by varying the user operable opening area on the windward side. The black lines are obtained by varying the user operable opening area on the leeward side.

Figure 5.

Predicted temperatures for case 1 in a sequence of warm days in July.

All temperatures in °C. Tout: outside air temperature. TaNW: average air temperature in the North West bay. TaSE: average air temperature in the South East bay. TSlab: average surface temperature of the concrete ceiling slab. MDN: BMS system window opening mode.

Figure 6.

Predicted comfort temperature and airflow direction for a sequence of warm days (case

1).

All temperatures in °C. The two bay temperatures shown (Tra-NW, SE) are obtained by calculating the average between the average air and mean radiation temperature in each zone. The gray squares labeled NW-WW signal cross-ventilation airflow entering the building in the NW bay and exiting in the SE bay.

Figure 7.

Indoor temperatures for a building with no BMS and uninformed users (case 5).
In this chart, MDN is the user operable opening level, from closed (0) to fully open (10).

Figure 8.

Temperatures in the two building bays for Cases 2-5.

Figure 9.

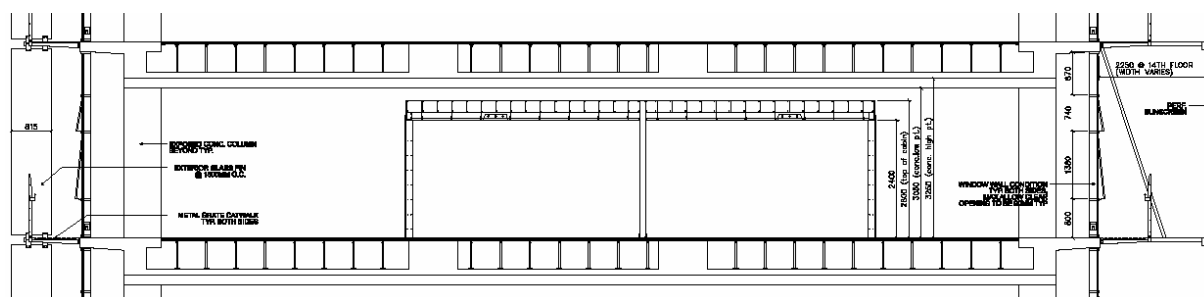
Effects of scrim transmissivity on the comfort temperature in the SE bay for a sequence of warm days in July.

Figure 10.

Effects of scrim transmissivity on the temperature in both bays during cold days.

Figure 11.

Percentage of hours above 24, 26 and 28°C during office operation hours (8am-6pm).



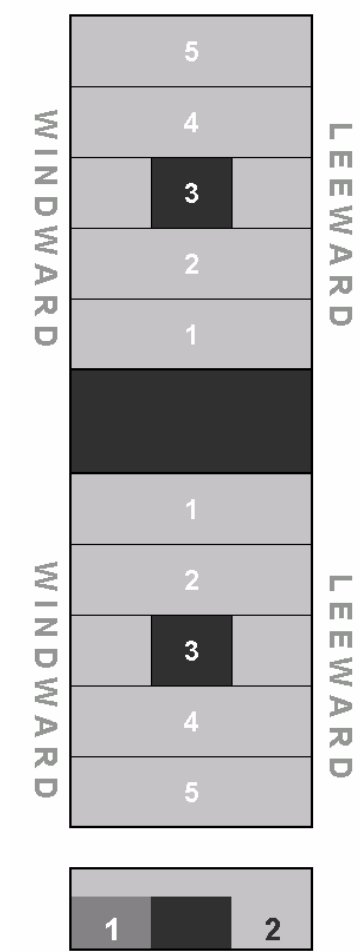


Figure 2.

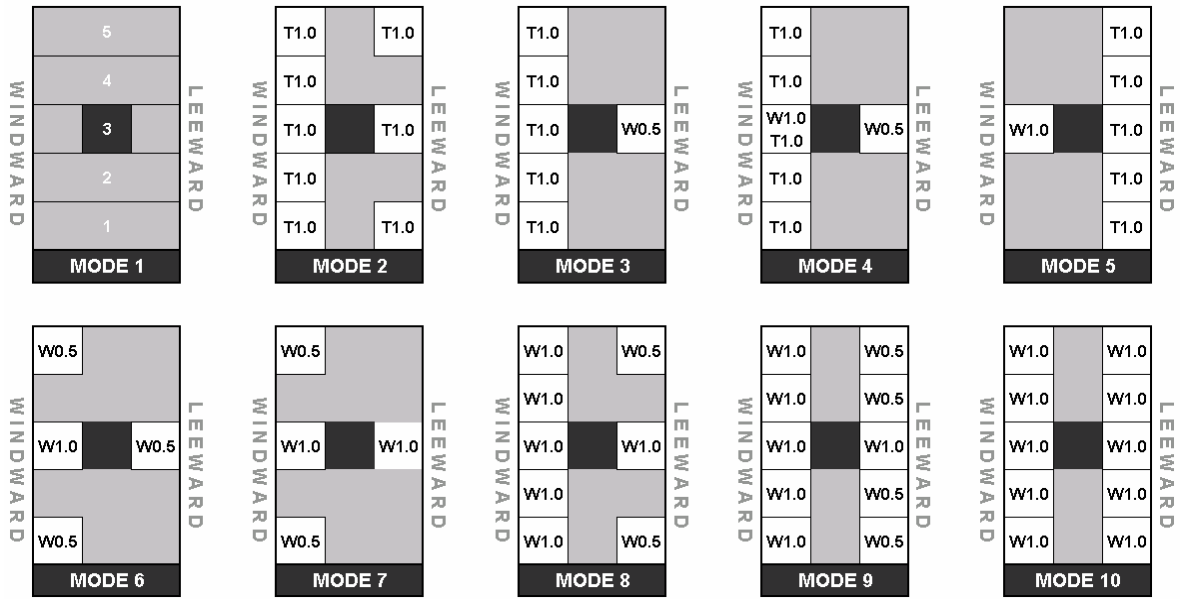


Figure 3.

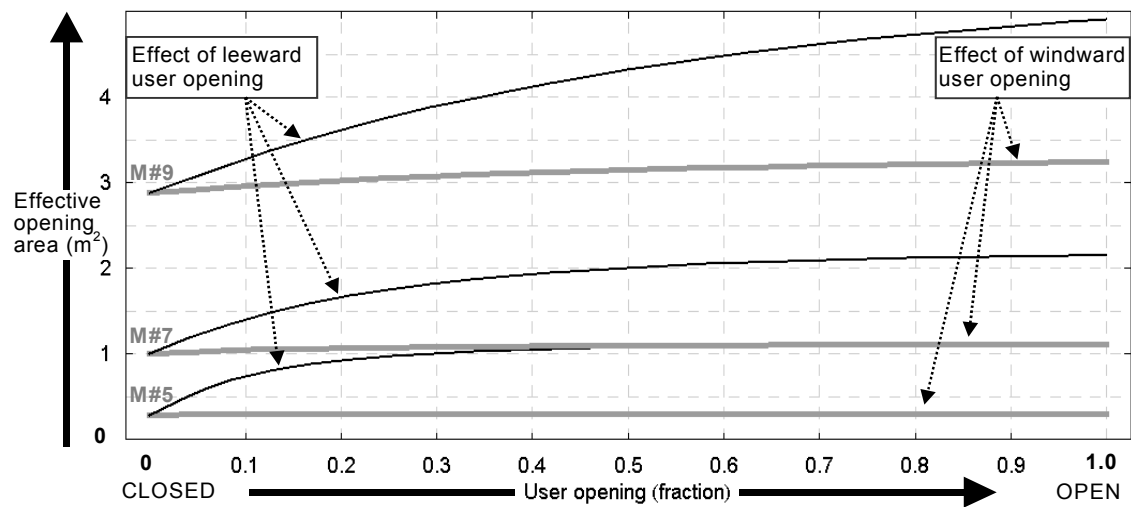
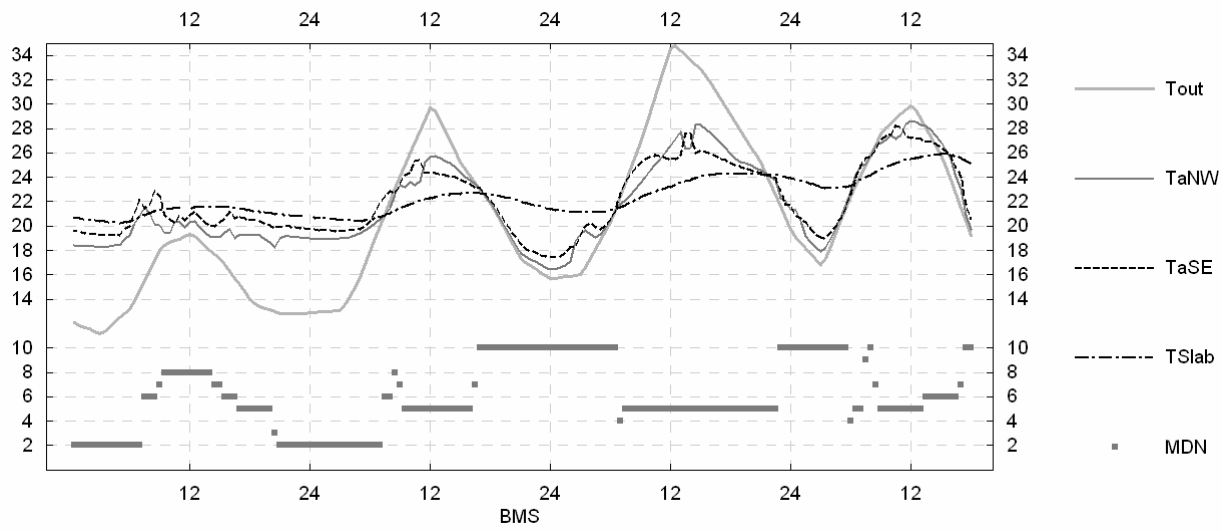


Figure 4.



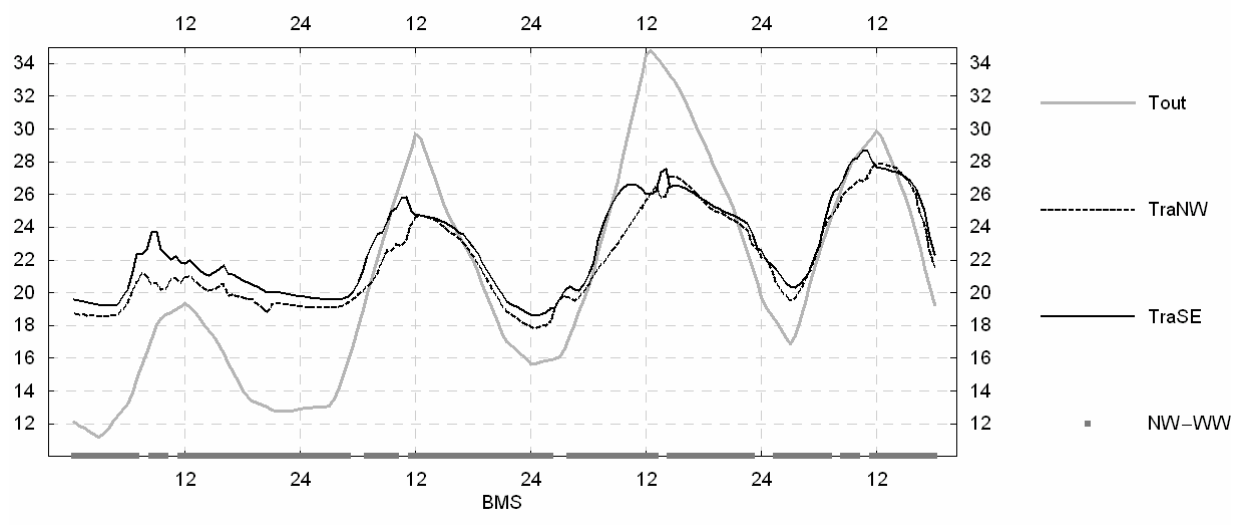


Figure 6.

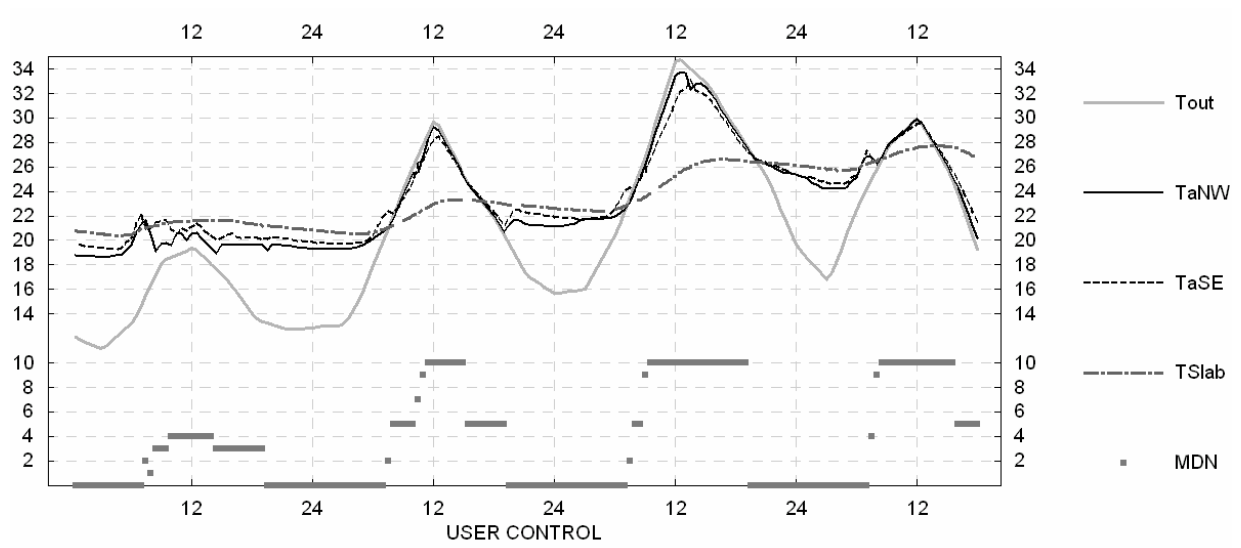


Figure 7.

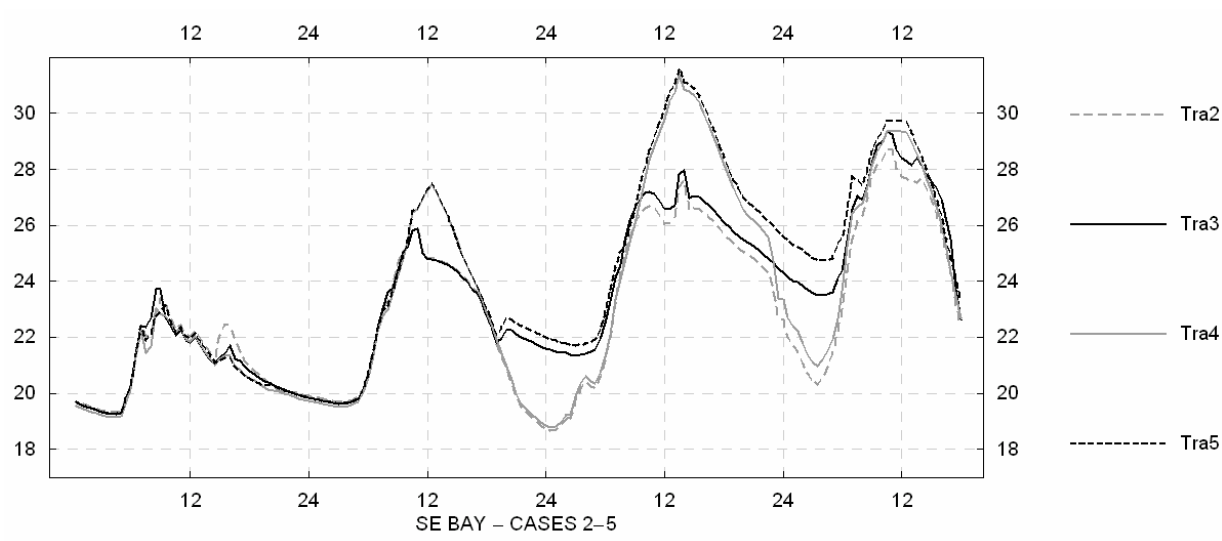


Figure 8.

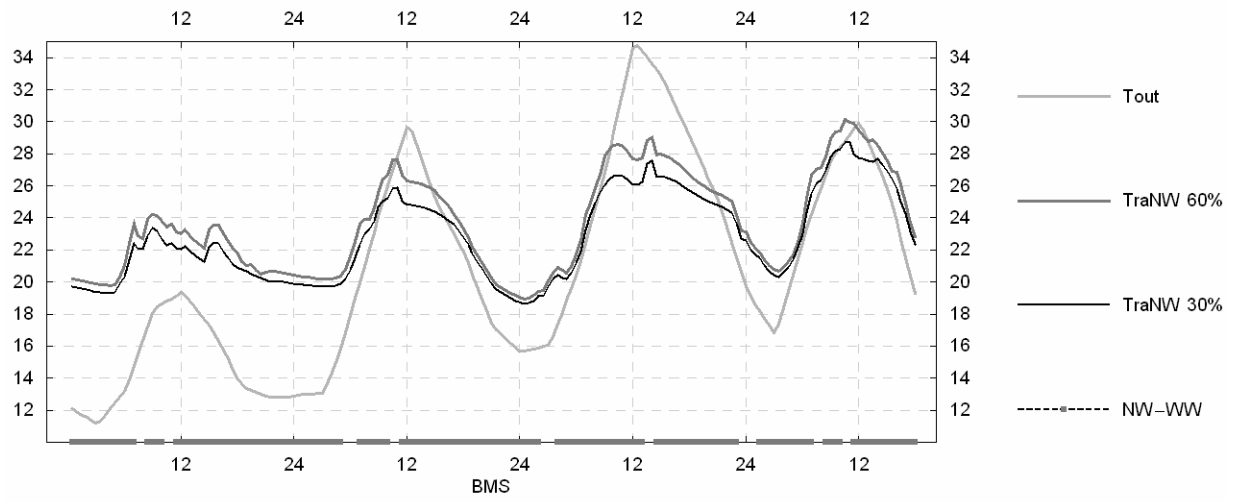


Figure 9.

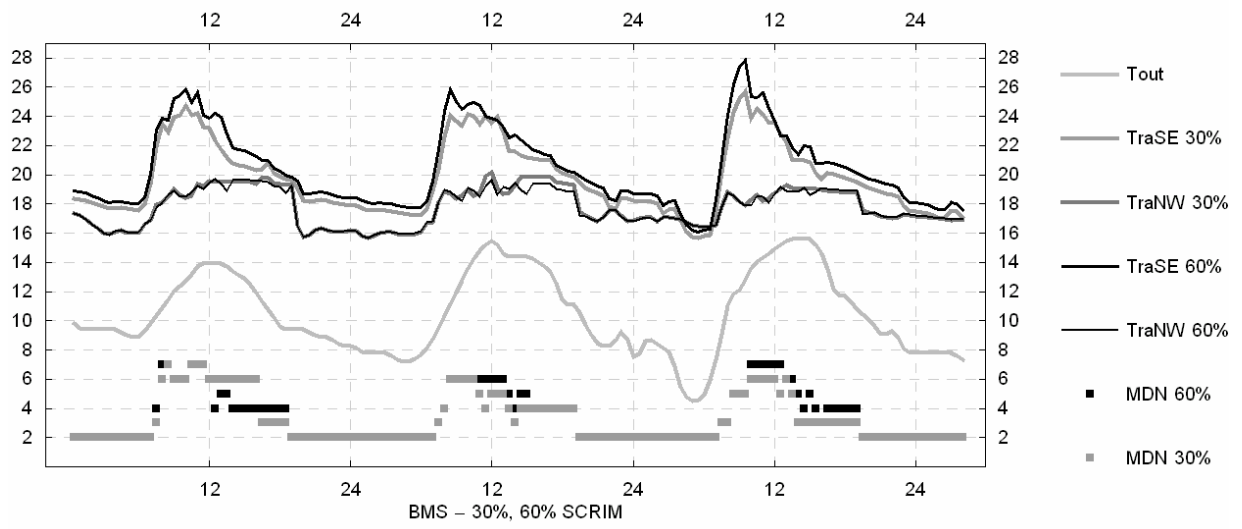


Figure 10.

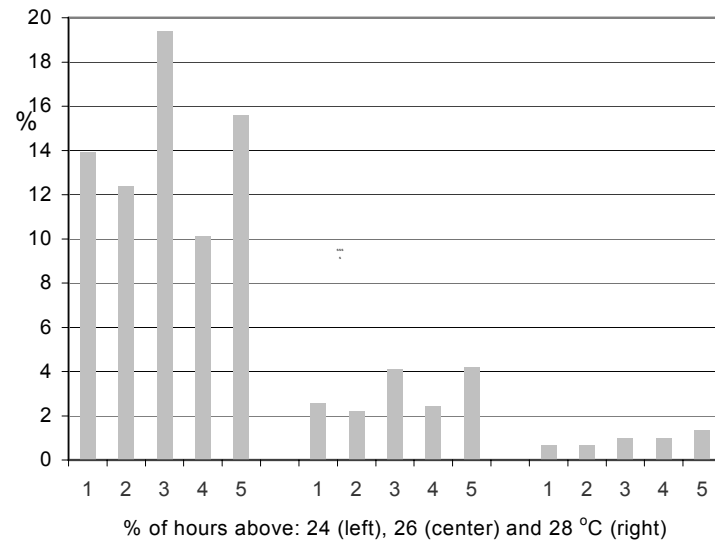


Figure 11.

Table 1. The four possible states of a floor during building operation hours.

WINDWARD	LEEWARD
Warm	Warm
Cold	Cold
Cold	Warm
Warm	Cold

Table 2. Characteristics of the opening modes. %Open is the effective opened area over maximum effective area. The average velocity V_{IN} at the inlet on the windward side is determined using (1), for a 10m/s outside wind, a pressure coefficient of 1 and a discharge coefficient (C_D) of 0.6. The predicted average velocity V_{OZ} in the occupied zone is obtained from CFD, for a 10m/s outside wind and a pressure coefficient of 1. V_{IN} and V_{OZ} are not shown for modes where it was not possible to define or when CFD predictions were not available.

Mode number	A_W/A_L	V_{IN}	V_{OZ}	% Open
1	-	-	-	0
2	2	2.7	0.89	3.4
3	0.5	-	-	6.7
4	1.3	3.8	-	22.2
5	3.7	1.6	0.53	7.3
6	4	1.5	0.50	13.7
7	2	2.7	0.89	25.3
8	2.5	2.3	0.76	52.5
9	1.7	3.1	1.02	72.8
10	1	4.3	1.42	100

Table 3. Division of the ten modes in three groups.

Situation	MODES
Storm	1 , 2
Heating/Rain	3 , 4
Mild/Cooling	5 , 6 , 7 , 8 , 9 , 10

Table 4. Flow rate decision rules as a function of measured temperatures.

Situation	Flow
$T_{IN} > T_{OUT}, T_S$	Increase
$T_{IN} < T_S, T_{OUT}$	Maintain, or increase if cold
$T_{OUT} > T_{IN} > T_S$	Decrease if warm, increase if cold
$T_S > T_{IN} > T_{OUT}$	Increase if warm, decrease if cold

Table 5. The five cases tested. Informed users(IU), uninformed users(UU) or no opening of the user operated windows are indicated in the last column.

Case	BMS	Night Cool	Users
1	Yes	Yes	No
2	Yes	Yes	IU
3	Yes	No	No
4	Yes	Yes	UU
5	No	No	UU

Table 6. Percentage of hours during daytime operation schedule that are above 24, 26, 28 and 30°C.

Case	Hours >24°C		Hours >26°C		Hours >28°C		Hours >30°C	
	NW	SE	NW	SE	NW	SE	NW	SE
1	2.2	14	0.6	2.5	0.12	0.64	0.00	0.18
2	2.2	12	0.7	2.2	0.17	0.64	0.00	0.19
3	3.9	19	1.0	4.1	0.29	0.95	0.00	0.30
4	2.9	10	1.2	2.4	0.45	0.96	0.11	0.38
5	4.2	16	1.4	4.2	0.52	1.3	0.16	0.49

Table 7. Estimation of discomfort due to excessive heat, for indoor temperatures above 24, 26, 28 and 30°C.

The values shown in the table are in Degree-Hour. Discomfort is estimated by adding the hours above the temperatures shown multiplied by the temperature differential.

Case	H . T >24°C		H . T >26°C		H . T >28°C		H . T >30°C	
	NW	SE	NW	SE	NW	SE	NW	SE
1	21.4	111.7	4.7	22.5	0.3	6.3	0.0	1.6
2	23.7	99.8	6.2	21.4	0.8	6.3	0.0	1.5
3	38.2	174.4	8.7	37.7	1.4	10.5	0.0	2.6
4	38.9	98.1	13.7	30.9	4.0	10.9	0.3	2.6
5	53.6	159.5	16.6	45.8	5.0	14.7	0.5	3.8

Table 8.

Table 6. Percentage of hours during daytime operation schedule that are above 24, 26, 28 and 30°C using a scrim with 60% solar/optical transmissivity.

Case	Hours >24°C		Hours >26°C		Hours >28°C		Hours >30°C	
	NW	SE	NW	SE	NW	SE	NW	SE
2	2.2	23.5	0.8	6.7	0.2	1.7	0.0	0.5
5	4.3	29.9	1.5	9.9	0.5	2.9	0.2	1.0

Proceedings of the 8th International IBPSA Conference, August 11-13, 2003, Eindhoven, Netherlands.

Design and Testing of a Control Strategy for a Large, Naturally Ventilated Office Building

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DESIGN AND TESTING OF A CONTROL STRATEGY FOR A LARGE, NATURALLY VENTILATED OFFICE BUILDING

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ABSTRACT

The design for the new Federal Building for San Francisco includes an office tower that is to be naturally ventilated. Each floor is designed to be cross-ventilated, through upper windows that are controlled by the building management system (BMS). Users have control over lower windows, which can be as much as 50% of the total openable area. There are significant differences in the performance and the control of the windward and leeward sides of the building, and separate monitoring and control strategies are determined for each side. The performance and control of the building has been designed and tested using a modified version of EnergyPlus.

Results from studies with EnergyPlus and CFD are used in designing the control strategy. EnergyPlus was extended to model a simplified version of the airflow pattern determined using CFD. Wind-driven cross-ventilation produces a main jet through the upper openings of the building, across the ceiling from the windward to the leeward side. Below this jet, the occupied regions are subject to a recirculating airflow. Results show that temperatures within the building are predicted to be satisfactory, provided a suitable control strategy is implemented uses night cooling in periods of hot weather.

The control strategy has 10 window opening modes. EnergyPlus was extended to simulate the effects of these modes, and to assess the effects of different forms of user behavior. The results show how user behavior can significantly influence the building performance.

INTRODUCTION

The control system development study presented in this paper continues previous work (Haves *et al*, 2003) on the design of the natural ventilation system for the new San Francisco Federal Building (SFFB). The definition of the control strategy for the natural ventilation system is critical to achieving good performance in the building. The requirements for this control strategy are:

- ability to control air speed in the occupied space;
- effective use of the building internal thermal mass for cooling;
- rational use of heating energy;
- control of indoor conditions during storm, rain and high wind periods;
- unintrusive and as simple as possible.

COMPONENTS OF THE INDOOR CLIMATE CONTROL SYSTEM

Figure 1 shows a section of a typical floor of the naturally ventilated portion of the building. In an earlier phase of the work, reported in a companion paper (Haves *et al*, 2003), it was determined that the favorable wind climate that exists in San Francisco produces sufficient cross-ventilation to maintain acceptable comfort. During episodes of hot weather, the building is ventilated at night to cool the exposed concrete ceiling slab, which serves as a heat sink for daytime heat gains. Buoyancy forces have a minor effect on the airflow in cooling mode.

Heating is provided by a perimeter baseboard system. There are nine trickle vents under selected baseboards on each bay, on each side of each floor. The main NW and SE facades are ~100% glazed. Although the windows on the SE façade are shaded by an external metal scrim, there is a significant amount of passive solar heating from these windows at the beginning of the day.

The building is controlled by a combination of user and automated window operation. The BMS has exclusive control over the baseboard heating system. As discussed below, the users can significantly change the total opening area, affecting the results of the automated control actions exerted by the BMS. In order to avoid continual control actions, which may be distracting for the occupants and cause unnecessary wear, the BMS will make adjustments approximately every 10 minutes. The exact interval will be determined as part of the process of commissioning the building.

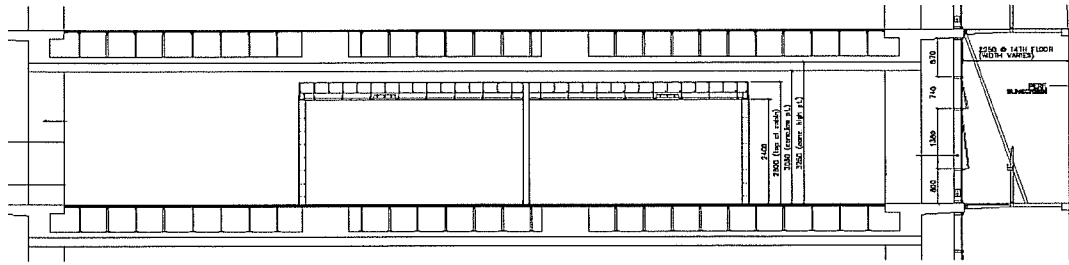


Figure 1. Section of a typical floor of the SFFB.

A section showing the NW bay (left), the SE bay (right) and the air-conditioned meeting rooms (middle). The lower operable windows visible in both bays are controlled by the users. The upper windows are controlled by the BMS. The user operated windows open 10cm, the BMS operated windows open 20cm. There are two user operated windows for every BMS operated window. There is a perforated stainless steel shading scrim that covers the South-East façade of the building.

VENTILATION STRATEGY

Whenever the wind-induced pressure is higher on one side of the building, air will flow into that side and out of the opposing side. The previous natural ventilation airflow analysis revealed an important characteristic of the crossflow ventilation (CV) airflow pattern. The incoming air attaches to the ceiling and partially “short circuits” the occupied zone of the windward bay, exiting through the windows in the leeward facade.

The proposed geometry of the user operated windows contributed to this short circuit effect, generating an inflow jet that attached to the windward user windows and joined the jet entering through the windows operated by the BMS. As a result, the windward side (WS) users had limited control over their local environment. This problem was addressed by proposing changes to the geometry of the user operable windows based on a CFD analysis of the airflow through the window (Linden *et al.*, 2002). A flow deflector, which directs the inflow from these openings into the occupied zone, was introduced. The flow pattern produced by the initial design resulted in leeward side (LS) users suffering the consequences of the control actions taken by WS users. With the WS users able to adjust their local flow conditions, by opening and closing a window that directs flow to their work area, the BMS can more easily address the needs of the LS users, using the short circuit of the air entering through the upper windows to produce a beneficial independence between the two sides (see Figure 2).

In addition to this separation, and as a result of the approximately symmetrical layout of the floor plan, we decided to simplify the control strategy by defining it in terms of Windward and Leeward, as opposed to NW and SE. Table 1 shows the four possible states that result from this approach. By

basing the control system on the wind direction, the number of system states is significantly reduced.

Care was taken to avoid air that had been heated by the baseboard system on the leeward side being exhausted through the adjacent trickle vents. For this reason, whenever the heating is on, only the trickle vents on the windward side are opened. Since height between the BMS and user operable windows is modest, stack driven ventilation is only important when the wind velocity is very low or parallel to the long axis of the building and the trickle vents are open.

Table 1. The four possible states of the occupied spaces on a particular floor during building operation hours.

WINDWARD	LEEWARD
Warm	Warm
Cold	Cold
Cold	Warm
Warm	Cold

Figure 2a shows the floor subdivision used to define the control zones. The basic control unit is one half of a floor (each floor has two BMS zones, one for each set of five “slices”, numbered 1-5 in Figure 2a). The labels: W and T stand for window (user operable) and trickle vents (under the baseboard system). The window opening strategy reflects the fact that the geometry of the inflow openings governs the airflow distribution and the consequent effectiveness of the removal of pollutants across the whole width of each side of the naturally ventilated part of the floor. The criteria used in defining the opening modes were:

- use distributed inflow openings to spread the inflow across the floor plan and reduce local velocities;

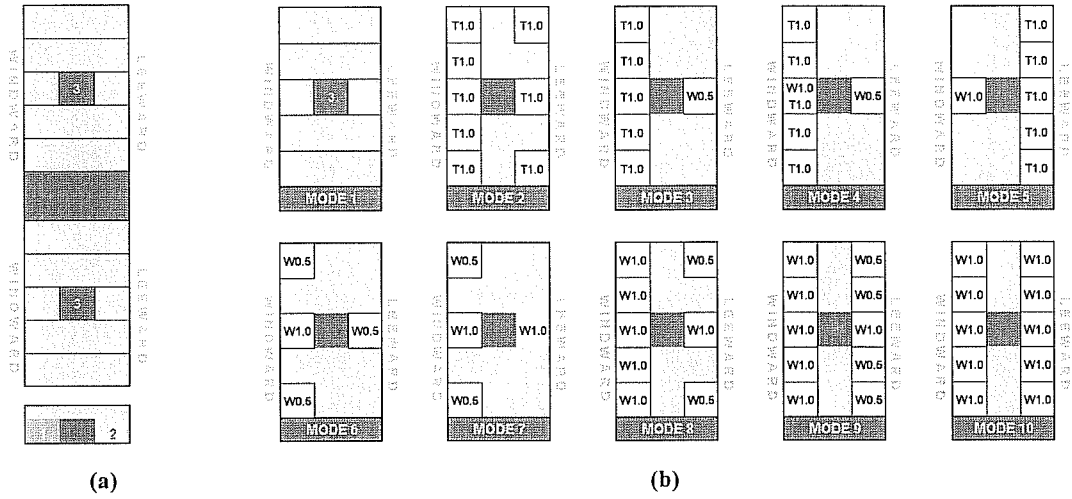


Figure 2.

a) Schematic layout of the control system on a typical floor. Each floor measure approximately 107x19m. Each half of each floor in the building is treated separately (in the figure, each set of 1-5 “slices”). Each slice contains four user operated and two BMS operated windows. The side view at the bottom of the figure shows the control structure, using the partial short circuiting of BMS window inflow into the windward zones (labeled 1). b) Schematic representation of the aperture modes. Each floor of the building is divided into two symmetrical sides. The figures show one half of one floor. The black square in the center of the figures is an elevator/service core that creates an obstruction to cross-ventilation airflow.

- use the outlet area to control the flow rate;
- minimize operation of openings (by ensuring continuity between opening modes, avoiding open-close-open sequences as the system increases opening area);
- minimize the number of window positions, in order to simplify the mechanical actuator system (three positions are used: closed, half-open and fully open).

The airflow control strategy was structured in an opening mode table, and the twenty BMS operable windows in each bay of the floor (two per “slice”, five “slices” on each side, leeward, windward), were grouped for simplicity. The grouping criterion was optimal flow distribution. Figure 2b shows a schematic representation of the ten opening modes used. The positions of the openings are shown as fraction of maximum opening size (between zero and one).

There are two groups of trickle vents on each bay: “slices” 1, 3 and 5, and “slices” 2 and 4. The window groups are: Group 1 containing the two motorized windows in slice 3, Group 2 contains the four motorized windows in slices 1 and 5 and Group 3 contains the four motorized windows in slices 2 and 4. Modes 3 and 4 use the windows on the leeward

side, in slice 3, to avoid exhaustion of warmed air through the leeward side trickle vents.

A mode table was organized in order to contain the opening modes ordered by effective opening area and weather/defensive criteria (see Tables 2 and 3 for grouping and characteristics of the modes). In Table 2, the column labeled “Open” refers to effective opening area. For a given pressure difference (ΔP), the effective opening area A^* and resultant flow rate are given by

$$F = A^* C_d \sqrt{\frac{2\Delta P}{\rho}}, \quad (1)$$

where

$$A^* = \sqrt{\frac{A_w^2 A_L^2}{A_w^2 + A_L^2}}.$$

The estimates of the indoor ventilation parameters A_w/A_L , V_{IN} and V_{OZ} presented in Table 2 show that the system has the desired characteristics, listed above. There is a continuous increase in opening size in each group of modes (see Tables 2 and 3). There is a set of modes that controls the inflow and average occupied zone velocities (Modes 5-8); Modes 9 and 10 are meant to be used when the wind is weak, or at night, when significant transfer between indoor air and the ceiling concrete slab is desirable.

Table 2. Characteristics of the opening modes. A_W is the opening area on the windward side, A_L is the opening area on the Leeward side, V_{IN} is the average velocity at the inlet on the windward side, using (1), for a 10m/s outside wind, a pressure coefficient of one and a discharge coefficient C_D of 0.6), V_{OZ} is the predicted average velocity in the occupied zone (from CFD, for a 10m/s outside wind and a pressure coefficient of one), and Open is the ratio of the effective opened area to the maximum effective area,

Mode	A_W/A_L	V_{IN} (m/s)	V_{OZ} (m/s)	Open (%)
1	-	-	-	0
2	2.0	2.7	0.89	3.4
3	0.5	-	-	6.7
4	1.3	3.8	-	22.2
5	3.7	1.6	0.53	7.3
6	4.0	1.5	0.50	13.7
7	2.0	2.7	0.89	25.3
8	2.5	2.3	0.76	52.5
9	1.7	3.1	1.02	72.8
10	1.0	4.3	1.42	100

Although the users have access to operable openings, it was decided that the BMS system would ensure 50% of the regulatory minimum outside air flow. The remainder will be provided by infiltration and the users, through their operable windows. Consequently, upper and lower limits are placed in the opening mode number depending on limiting factors: a lower limit is used in order to ensure minimum outside air, an upper limit is used whenever the wind is strong, during rain periods or when the baseboard heaters are turned on in both bays.

The first high wind opening limiting mode is triggered by:

If $\Delta P > 60$ or $V_{wind} > 20\text{m/s}$ then the mode number cannot go above 8.

The second high wind opening limiting mode is triggered by:

If $\Delta P > 130$ or $V_{wind} > 25\text{m/s}$ then the mode number cannot go above 6.

The storm mode is triggered by:

If $\Delta P > 300$ or $V_{wind} > 30\text{m/s}$ then the mode number cannot go above 2.

Additional rules include:

If heating is on in both bays, or it is raining then the mode number cannot go above 4.

If both sides are in cooling mode then the mode number cannot go below 5.

Table 3. Division of the ten modes in three groups.

Situation	MODES
Storm	1 , 2
Heating/Rain	3 , 4
Mild/Cooling	5 , 6 , 7 , 8 , 9 , 10

INSURING MINIMUM OUTSIDE AIR

With the objective of having the BMS system ensure 50% of the minimum outside air, we establish a decision process based on:

1. the measured the outside pressure difference ΔP ;
2. an estimate of stack pressure (whenever the trickle vents are open, in the current control system, this is equivalent to the heating being turned on, see modes 2-4 in figure 1);
3. the fluctuating wind velocity pressure (in order to prevent excessive opening size when the wind is parallel to the building and the average pressure difference measurement (ΔP) is close to zero but the transient ventilation is significant).

The BMS estimates the total available pressure and determines the minimum opening size and the corresponding mode numbers between 3 and 10. When there is a storm (the system is in Modes 1 or 2) we rely on infiltration and user adjustment to provide minimum outside air. Buoyancy will only be considered when the heating is on in both bays (which implies the trickle vents are open).

The total pressure difference (ΔP_T) available to drive the flow is the sum of the pressures discussed above

$$\Delta P_T = \Delta P + \text{HOF} \left(0.088 \left| \frac{T_W - T_L}{2} - T_{OUT} \right| \right) + 0.015 U_{WIND}^2 \quad (2)$$

where U_{WIND} is the outside wind speed and HOF is a software "flag" that signals the buoyancy component should be considered.

The third term in (2) is based on an experimental correlation for airflow in a building exposed to an incoming wind parallel to equal openings on opposed envelope surfaces (Etheridge, 1979). In order to simplify the estimation of ΔP_T , the effects of unequal opening areas on the two bays are ignored. In addition the transient pressure (third) term is not dependent on wind direction. This is an acceptable approximation because, whenever the wind is not parallel to the openings, the first term is an order of magnitude larger.

IMPACT OF USER WINDOW CONTROL

The user operable window area is approximately equal to the BMS controlled area; therefore, users can significantly change the total effective opening area (see (1)). The lower windows are exclusively under user control, and users can, for example, increase the effective opening size ten times when the system is in Mode 5 or approximately double the effective area when in Mode 10.

If user control is not considered when designing the control strategy, two main problems can occur:

- (a) users on one of the two sides could significantly affect the climate control on the other side, and
- (b) incorrect user control could lead to poor overall system performance, producing overheating of the interior space and concrete slab in summer, and allowing heat to escape to the outside in winter.

The impact of user opening level on the effective opening area decreases with increasing opening mode number. On warm days, whenever the control objective is to make optimal use of the cooled concrete slab, user opening can result in higher, and often uncomfortable, indoor temperatures.

Clearly, the more general consequences of user behavior cannot be addressed by the control system. Therefore, appropriate information on building behavior and on adequate actions in different situations must be provided to the users.

By controlling the airflow rate using the size of the outlet, and by making the flow controlled by WS users affect primarily the WS users, significant automatic control over the conditions of the LS users was achieved. When WS users open their windows, the overall flow does not change significantly if the high level WS windows are already open. However, when these users open their windows, the existing airflow and inflow is partially displaced from the upper (BMS controlled) openings to the user operated windows (in the proportions of the relative opening areas). In this way, the WS users achieve the desired change, more outside airflow through their working area, without significantly changing the leeward side conditions.

However, adjustments by the LS users have a significant effect on the airflow rate. In view of the previously mentioned partial short circuiting of the inflow and the ability of WS users to adjust their local conditions, we conclude that the asymmetry in flow control is a beneficial feature of the system.

MODELING USER BEHAVIOUR

Modeling user behavior is a complex but essential task for the present study. In order to simulate the performance of the indoor environment control system with both BMS and user actions, two types of user behavior were defined.

- **Uninformed users (UU):** this type of user is modeled so that user behavior is totally independent of BMS actions. If the conditions are warm, the user operable windows open sequentially (10% in each control time step, 10 minutes), up to 50% for indoor temperatures between 22 and 25°C, and up to 100% for temperatures above 25°C. If the conditions are cold, below 19°C, the user operable openings close by 5% each time step. On a typical day, when the air temperature in either of the two bays goes above 22°C, users will open the windows, the windows will then remain open until the temperature on one of the sides drops below 19°C, or until the end of the workday, when users always close their windows.

- **Informed users (IU):** this type of user follows the BMS actions in an ideal way. Users only open their windows when the BMS is in one of the mild modes. Informed users follow the same decision and action trends as uninformed users but limit their opening amplitude in accordance to the BMS mode that is currently being used (linearly, from 0% in Modes 1-5 to 100% in Mode 10). In addition, whenever the BMS system uses night cooling, informed users will leave their windows fully opened overnight.

These two user behavior scenarios allow us to model overall control system performance (users with BMS) in two extreme situations: positive and negative interaction between users and the BMS system.

CONTROLLING INDOOR TEMPERATURE

Table 1 showed the four temperature states that can occur in the two control zones of the building. We now proceed to describe and analyze the control strategies and rules used in each case.

Both sides cold. When both sides are cold, the heating system is on and the ventilation system will tend to minimum outside air in a progressive way, by reducing the window opening mode by one in each control time step.

Both sides warm. In order to clarify the control principles used during daytime in the warm season, we present here a first order analysis of system behavior. For this analysis we make two approximations.

- (i) The only thermally active internal surface is the concrete ceiling slab. This approximation is adequate since the remaining internal surfaces in the space

have low thermal mass and, therefore, tend to behave in an approximately adiabatic way, closely following the internal air temperature.

(ii) The internal air is fully mixed in each bay, which is a significant approximation that is only acceptable for a first order analysis. Also, for control purposes, during warm periods, the BMS system uses a single temperature (the highest of the two bays) to represent indoor conditions.

In these conditions, the equation that represents energy conservation in a control zone (one half of one floor, see Figure 2) is

$$h A_s (T_{IN} - T_s) + \rho c_p F (T_{IN} - T_{OUT}) = G, \quad (3)$$

where h is the average heat transfer coefficient, T_{IN} is the fully mixed indoor temperature, T_s is the concrete ceiling slab average surface temperature, T_{OUT} is the outside temperature, c_p is the heat capacity of air at constant pressure, ρ is the density of air, F is the volumetric flow rate and G is the sum of the other heat gains (solar, internal and heat conduction through the envelope). The solution to (3) is

$$T_{IN} = \frac{1}{1 + \theta} \left(T_s + \theta T_{OUT} + \frac{G}{h A_s} \right) \quad (4)$$

where $\theta = \rho c_p F / h A_s$ is the normalized air flow rate.

Once a building is in operation, all the temperatures in this expression can be measured and used to make decisions on the single adjustment parameter available, the flow rate F . The gains, the value of the heat transfer coefficient and exposed area are generally unknown, although, in an office space in mild climate, we expect the gains to be positive during the mild/warm season.

Qualitative analysis of (3) reveals that when F is increased, the parameter θ increases and T_{IN} tends to T_{OUT} . Conversely, decreasing θ brings T_{IN} closer to T_s . The unknown parameter G influences internal conditions (increased G results in increased T_{IN}), but, by measuring T_{IN} we can obtain an indirect measurement of G , and there is no decreased control ability from not knowing the internal gains. Table 4 presents the warm weather control rule map that was used.

Windward cold, leeward warm: as seen in the simulation results below, this situation often occurs in the early morning of the winter and mild season days. This is one of the situations where the interaction between the two sides must be considered. To meet the need for cooling in the leeward side the ventilation mode is increased by one. In order not to increase the cooling needs of the LS users, but still address the need for heating on the windward side, the windward heating set point is set to 18°C.

Windward warm, leeward cold: this case is the contrary of the previous case, but is not as problematic because the WS side users can address their needs by opening their user window (increasing local flow rate) without greatly affecting the overall flow rate. For these reasons, in this situation, the control system will reduce the aperture mode by one and set the leeward heating set-point to a relatively high value (21°C), to ensure heating on this side.

Night cooling: night cooling of the concrete ceiling slab will be done whenever the average indoor temperature during the warmer period of the day (11 am - 4 pm) is above 24°C. When night cooling is requested by the temperature control routine the ventilation system uses the maximum allowed opening mode until the slab temperature is below 19°C or until the early morning of the following day (7 am).

Table 4. Flow rate decision rules as a function of measured temperatures.

Situation	Flow
$T_{IN} > T_{OUT}, T_s$	Increase
$T_{IN} < T_s, T_{OUT}$	Maintain, or increase if cold
$T_{OUT} > T_{IN} > T_s$	Decrease if warm, increase if cold
$T_s > T_{IN} > T_{OUT}$	Increase if warm, decrease if cold

In future, the design team intends to incorporate weather prediction information in the control system, basing the decision to night cool on the next days predicted weather as well heat storage in the fabric during the previous day.

SIMULATION

In order to develop and test the low energy cooling system and its BMS control strategies, the behavior of the building and users was modeled using EnergyPlus, which incorporates the COMIS interzone airflow model (Huang et al, 1999). The model implemented to test the initial design principles (Haves et al, 2003) was the starting point for the model used in the simulations presented below. This model uses four distinct zones: the two bays (NW and SE), the meeting room in the middle of the floor plan and the space above the meeting rooms (see Figures 1 and 2). The simulation used pressure coefficients measured in a boundary layer wind tunnel (RWDI, 2002). Pressure coefficients representative of average wind exposure in the naturally ventilated portion of the building were chosen. Since only floors 6 and above are naturally ventilated, and adjacent buildings do not reach this height, all floors have sufficient wind exposure.

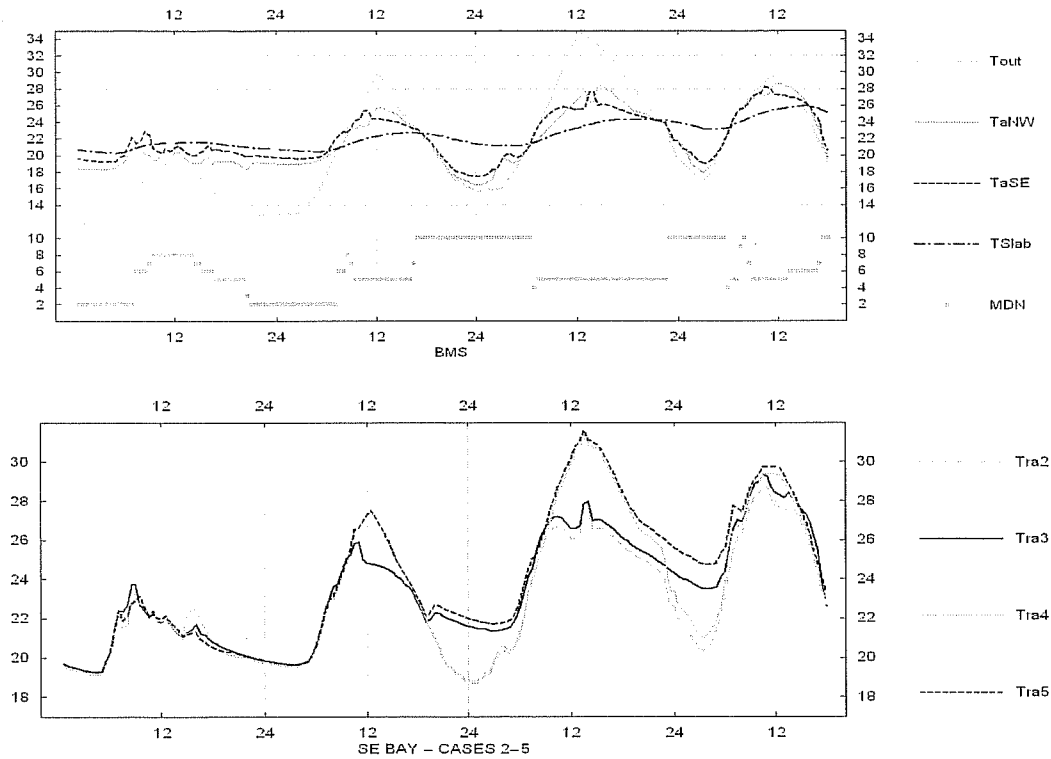


Figure 3. Predicted temperatures for case 1 in a sequence of warm days in July

All temperatures in °C. Tout: outside air temperature. TaNW: average air temperature in the North West bay. TaSE: average air temperature in the South East bay. TSlab: average surface temperature of the concrete ceiling slab. MDN: BMS system window opening mode. Tra2-5: the mean of drybulb air and mean radiant temperature in the SE bay for cases 2-5.

The modularity of EnergyPlus allowed for the inclusion of a custom control subroutine (a module) that was used to simulate and tune the operation of the BMS system. The transmissivity of the metal shading scrim on the SE façade (see Figure 1) was set to 30%. The five cases simulated are shown in Table 5. Two typical mean weather years for San Francisco were used (a TMY and a TMY2).

Table 5. The five cases tested. First column: case number. Second: whether the case uses BMS control during the day. Third: whether the system uses night cooling. Four: type of user control, informed (IU), uninformed (UU) or no opening of the user operated windows.

Case	BMS	Night Cool	Users
1	Yes	Yes	No
2	Yes	Yes	IU
3	Yes	No	No
4	Yes	Yes	UU
5	No	No	UU

RESULTS

Figure 3 shows the predicted temperatures in the two bays and in the surface of concrete ceiling slab, for case 1 during a sequence of warm days in July. The results are plotted as 30 minute averages. The BMS system made decisions (turn on-off heating, change window modes) every 10 min. The first day shows typical behavior in a mild day. Between 10am and 2pm the BMS system uses outside air to remove internal heat gains. The second day is a typical warm day, and the BMS system selects the minimum daytime mild/warm mode (Mode=5). The air temperature in the SE bay (TaSE) has two phases during the day: above TaNW during the morning, as a result of solar gains in the SE façade, and below TaNW in the afternoon as a result of increased slab cooling effect in this bay. For NW incoming wind, the air moves in contact with the ceiling slab until it enters the SE bay. During the unoccupied night period of the second and third days shown, the system performs night cooling by selecting the maximum opening mode (Mode=10). The increase in slab

temperature is visible. Temperatures labeled “ra” are the average “comfort” temperature (average of the mean radiant and air temperatures) in the two bays. As expected, air flows from NW to SE for a majority of the hours. The consequence of change in airflow direction is clearly visible at 1pm on the third day. As a result of a wind direction change the mean of drybulb air and mean radiant temperature changes, with a consequent increase in the SE as airflow cooled by the slab is replaced by warmer outside air.

Table 6 presents indicators of indoor climate control system performance for the five cases shown in Table 5. It is clear that uninformed users (cases 4 and 5) can have a significant negative impact in indoor climate conditions. According to our assumptions, uninformed users make limited use of the cooled slab and consequently warm their indoor environment. Because these conditions are not frequent, there is no substantial impact on system performance. Since the user operable area is comparable to the BMS controlled area, the impact extends to case 4. The absence of night cooling results in a 1K increase in the temperature on the warmest days.

Table 6. Percentage of hours during daytime operation schedule that are above 24, 26, 28 and 30°C. Columns labeled NW and SE refer to the two building bays. The cases correspond to those listed in Table 5.

Case	H >24°C		H >26°C		H >28°C		H >30°C	
	NW	SE	NW	SE	NW	SE	NW	SE
1	2.2	14	0.6	2.5	0.12	0.64	0.00	0.18
2	2.2	12	0.7	2.2	0.17	0.64	0.00	0.19
3	3.9	19	1.0	4.1	0.29	0.95	0.00	0.30
4	2.9	10	1.2	2.4	0.45	0.96	0.11	0.38
5	4.2	16	1.4	4.2	0.52	1.3	0.16	0.49

CONCLUSIONS

The results of the simulations show that the low energy indoor climate control system developed is expected to have excellent performance. The use of a window aperture mode table, in conjunction with the Windward-Leeward based control strategy, resulted in a clear and effective natural ventilation system. Analysis using simple heat balance calculations provides a basis for the simple temperature control strategy adopted.

Night cooling and optimal use of the chilled slab during the day is an appropriate strategy to deal with the warmest periods. As a result of the significant user controlled aperture area, the more general consequences of user behavior cannot be addressed by the control system. Clearly, information for the

users on building behavior and on appropriate actions in different situations is important. However, simulations of different control strategies showed that the operation of the BMS always improves indoor conditions, even when occupant behavior is counterproductive.

ACKNOWLEDGEMENTS

Rick Lasser, David Summers and Michael Holmes (all from Arup & Partners) provided assistance and advice at various stages of the work. This work was supported by the U.S. General Services Administration and by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Federal Energy Management of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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